

# Research on Streamlining Seismic Safety Evaluation of Underground Reinforced Concrete Duct-Type Station

## -Part –3. Analytical Simulation by RC Macro-Model and Simple Soil Model -

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### ABSTRACT

We have been conducting a research to obtain the verification data concerning the performance of RC duct-type underground structures subject to strong earthquakes. In this paper, we simulated large-scale laminar shear box excitation test [1] by a dynamic nonlinear FEM and discussed the validity of modeling, by which RC member and soil are defined as hysteresis dependent models (RC : Axial force dependent degrading tri-linear model , soil : Ramberg-Osgood model), using joint elements to simulate the interaction along the interface of two materials including the slippage and separation between soil and RC structure.

As a result, the proposed analytical method was confirmed to predict the deformational characteristics of soil and RC structure as well as damages of RC structures in relation to verification of seismic performance within a practical accuracy.

### INTRODUCTION

Since the 1995 Great Kobe Earthquake, appropriate seismic safety assessment of infrastructures has been posing an urgent issue requested from the public. In particular, as for underground structures, verification of the seismic safety was a pressing need in the face of shear failure happened to the center pillars in subway Daikai-station. In view of the situation, review as well as upgrading of various structural design codes has been attempted and some of them have been revised from limit states design to performance verification design.

In this paper, we aim at proposing a practical method of nonlinear structural analysis in order to verify seismic performance. The method proposed here is classified as method A in the definition described in Part-1. Considering convenience in practical use, soil and structure were represented by simple models to help reduce CPU time, which led to adoption of macro hysteresis dependent models. In addition, it was anticipated that influence of interaction between soil and structure was pronounced due to strong earthquakes. A simple model (joint elements) was defined as boundary condition to reproduce slippage and separation between the two materials.

To confirm the applicability of this macro model, we simulated the shaking table tests with embedded RC duct-type model structures to be compared with experimental results, and discussed validity with respect to verification method of seismic performance.

### OUTLINE OF EXPERIMENT AND ANALYSIS

#### Outline of Large-scale Shaking Table Tests

In the large-scale laminar shear box excitation experiment, RC duct-type structural model was embedded in dry sand as illustrated in Fig.1. One was the case in which its bottom slab was firmly fixed to the base-plate of shaking table (hereafter called “fixed case”). The other

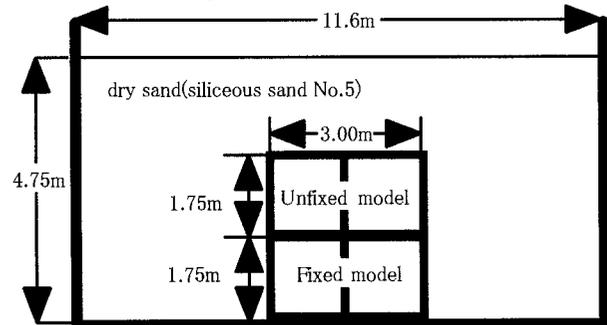


Fig.1 Arrangement of RC Boxes in the Laminar Shear Box

model was placed 1.5m above the base plate (hereafter called “unfixed case”). RC structure was two-box-duct-type specimen with a scale of 1 to 2.5 with respect to actual structures. Specification of RC members and their material properties are given in Tables 1 and 2, respectively. In particular, RC structure was designed as  $G_s$  (shear stiffness of whole RC structure) /  $G_g$  (shear stiffness of soil) = 0.20 to facilitate plastic deformation of RC structure. Input acceleration data adopted in the excitation tests were based on N-S component of records observed in the campus of Kobe University at the time of Great Kobe Earthquake on 17 Jan. 1995. The maximum acceleration was changed to about 1100 Gal, and the time scale was compressed by a factor of 1/2.

**Table 1. Specification of Section of RC Structure**

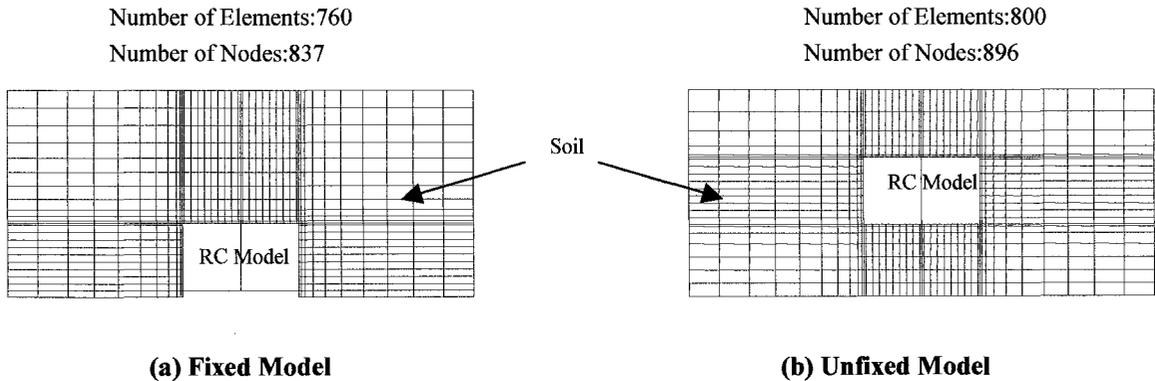
Index			Value
Width of RC member	B	[m]	1.00
Length of RC member	L	[m]	3.00
Height of RC Structure	H	[m]	1.75
Width of RC member	h	[m]	0.30
Concrete Cover	d	[m]	0.01
Reinforcement ratio	$p_t$	[%]	0.56

**Table 2. Material Properties of Concrete and Rebar**

		Index		Value
Concrete	Young's Modulus	$E_c$	[MPa]	$2.64 \times 10^4$
	Compression Strength	$f'_c$	[MPa]	32.36
	Tensile Strength	$f_t$	[MPa]	2.34
Rebar	Young's Modulus	$E_s$	[MPa]	$1.76 \times 10^4$
	Yield Strength	$\sigma_{sy}$	[MPa]	257.60

### 1) Analytical Model

2D-FE mesh for analysis was generated considering the size of laminar shear box as sketched in Fig.2. The side boundary condition was idealized by horizontal rollers with a mass representing the effect of inertia force caused by the frame of laminar shear box. The upper boundary was made free, and the bottom one was fixed.



**Fig.2 Finite Element Mesh for Overall System**

### 2) Modeling of Soil [2]

To express the nonlinearity of RC members a tri-linear moment-curvature model was adopted, and for soil Ramberg-Osgood model (hereafter called “R-O model”) was incorporated in view of matching complexity with the RC model used.

$$\gamma = \frac{Su}{G_0} s \left( 1 + \alpha |s|^\beta \right) \quad (1)$$

in which  $s$  is normalized shear stress,  $\gamma$  is shear strain,  $S_u$  is shear strength,  $G_0$  is initial shear modulus,  $\alpha$  is parameter depending on failure strain,  $\beta$  is parameter specifying the shape of skeleton curve

(i)  $G_0$

$G_0$  was obtained from following expression using measured  $V_s$  and  $\rho$  in the laminar shear box.

$$G_0 = \rho V_s^2 \quad (2)$$

in which  $V_s$  is velocity of secondary wave in sand, and  $\rho$  is the density of sand.

(ii)  $\alpha$

In R-O model, it was difficult to estimate the reduction of shear stiffness of soil in the whole shear strain range keeping a consistent accuracy. Therefore, we paid attention to maximum shear strain of soil ( $\gamma = 3.0\%$ ) which was measured in the excitation test, and defined as the strain at failure ( $\gamma_f$ ). The shear stress corresponding to that strain was provided from the result of element tests of soil. Reference strain ( $\gamma_r$ ) and coefficient  $\alpha$  were calculated from Eq. (3) and (4), respectively.

$$\gamma_r = \frac{\tau_f}{G_0} \quad (3)$$

$$\alpha = \frac{\gamma_f}{\gamma_r} - 1 \quad (4)$$

(iii)  $\beta$

Coefficient  $\beta$  was determined from the regression analysis.

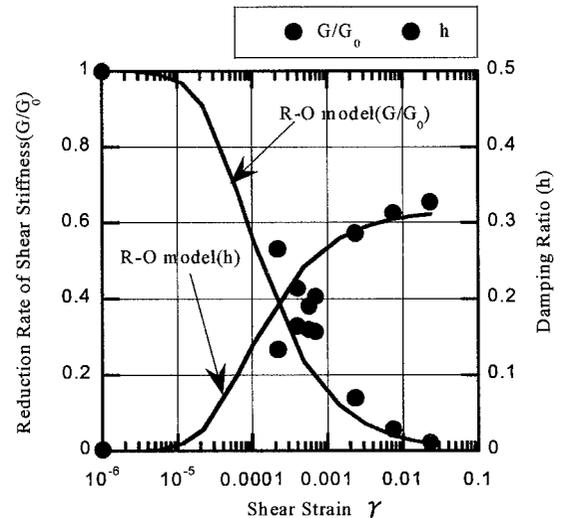
$$h = \left( \frac{2}{\pi} \right) \left( \frac{\beta}{\beta + 2} \right) \left( 1 - \frac{G}{G_0} \right) \quad (5)$$

where  $h$  is damping ratio of soil.

To define the hysteresis loop, we applied Masing Rule [3] in which  $n$  was given as 2. A R-O model fitting with experimental results is depicted in Fig.3 for the case of mean effective stress of 20kPa.

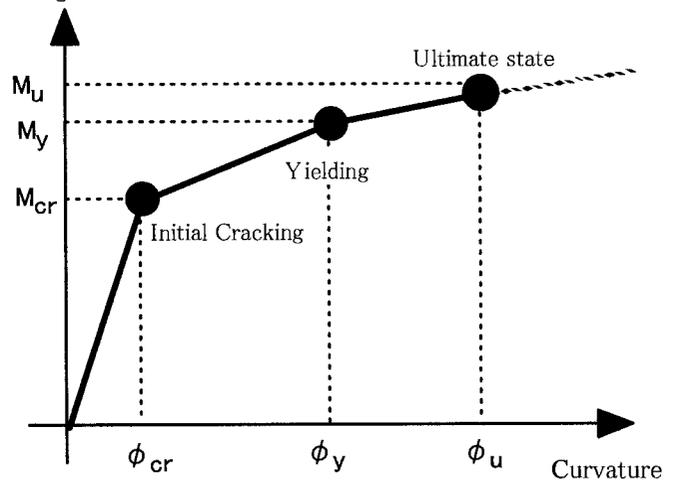
### 3) Modeling of RC Member [4]

Skeleton curve defining relationships between bending moment and curvature for RC member was modeled by axial force dependent degrading tri-linear model. Here, three characteristic points corresponded to initiation of crack, yielding in rebar and compression



**Fig.3 Dynamic Properties and R-O Model for Siliceous Sand No.5**

Bending Moment



**Fig.4 Axial Force Dependent Tri-linear Model for RC Member**

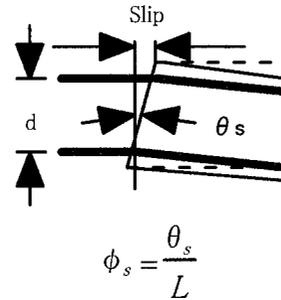
failure of concrete, respectively and the values were calculated by section analysis subjected to simultaneous axial force and moment (Fig.4).

In the corner regions of RC members, pulling-out of rebar was observed, which influenced overall load - displacement relationships of RC structure. Taking this effect into account, the position of the second characteristic point (yielding in rebar) was modified which was based on relationships caused by pulling-out due to slippage between rebar and concrete. The slippage was expressed by the following equation. [5]

$$\text{Slip} = \epsilon_s (2 + 3500 \epsilon_s) \left( \frac{f'_c}{20} \right)^{-2/3} D \quad (6)$$

$$\phi_s = \frac{\theta_s}{L} = \frac{\text{Slip}}{dL} \quad (7)$$

$$\phi'_y = \phi_y + \phi_s \quad (8)$$

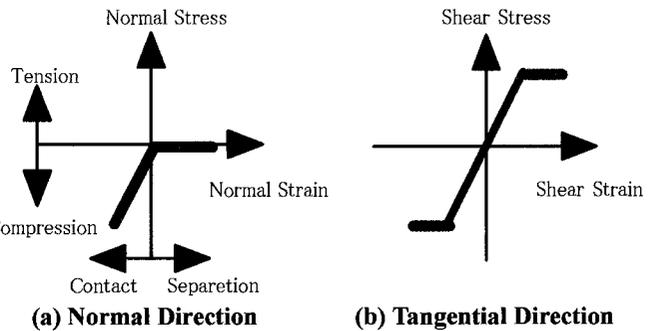


**Fig.5 Modeling of Pulling-out of Rebar**

In the equations above the symbols are defined as follows;

Slip : slippage due to pulling-out,  $\epsilon_s$  : strain in rebar,  $f'_c$  : compression strength of concrete,  $D$  : diameter of rebar,  $\phi_s$  : curvature generated by pulling-out,  $L$  : length of finite element,  $d$  : spacing of rebar,  $\phi'_y$  : modified curvature at section of yielding,  $\phi_y$  : original curvature at section of yielding

Nonlinearity due to shear stiffness degradation of RC members was not considered since substantial shear deformation did not occur thanks to ample arrangement of web reinforcement.



**Fig.6 Constitutive Relationship of Joint Element**

#### 4)Modeling of Interaction between Soil and Structure

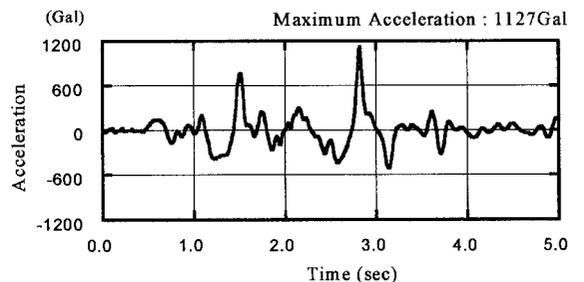
In order to consider slippage and separation between soil and structure, joint element was inserted between them, which was formulated to follow Mohr-Coulomb law (Fig.6). Here, cohesion and friction angle in joint element was defined as 0 and 23.4°, respectively[6].

The dynamic response analysis was executed by using time history of response acceleration measured at the floor of the laminar shear box (Fig.7).

### ANALYTICAL RESULT AND DISCCUSIONS

#### Behaviors of Combined RC and Soil Systems

Fig.8 depicts maximum value distributions of horizontal displacements in whole system along the height of the laminar box compared with the corresponding experimental ones. Analytical results agreed with the experimental ones in the range where the RC structure was buried with the exception that analytical value was a little smaller than that of experiment in the case of unfixed model. This difference could be attributed to the following facts; That is, 1) In the experiment the horizontal displacement of side boundary was measured at the frame of laminar box, which did not necessarily represent the displacement



**Fig.7 Time History of Floor Response Acceleration Employed for Analysis (Fixed Case)**

of soil itself, and 2) Stable dynamic movement of soil was not available due to lower confinement pressure in the upper region, which was aggravated by extremely higher excitation of over 1000Gal. Looking at the overall comparison between analytical and experimental results for displacements, it may roughly be said that the assumptions employed in the dynamic modeling were appropriate.

### Behavior of RC Structure

#### 1) Overall Displacement of RC Structure

Analytical results of the time history of relative horizontal displacements between top and bottom slabs were compared with the experimental ones in Fig.9 for fixed and unfixed cases. In the case of unfixed model, in spite of  $G_s/G_g \ll 1.0$ , the effect of slippage and separation between soil and structures had a pronounced influence on overall deformation of RC structure. However, in both cases, analytical results agree well with experimental ones when joint elements were incorporated except for residual displacements, which cannot be dealt with by the analytical model applied.

#### 2) Verification of Judgment of Yielding in RC Member

In the experiment, when steel strain exceed yielding strain, we judged the steel yielded. The vertical axis on the right hand in Fig.9 represents steel strain normalized by yielding strain. In the analysis, however, the moments are defined in the vertical axis on the left hand in Fig.10, being normalized by yielding moment. Thus, we can compare the yielding strain and moment on the same scale for the sake of simplicity. As can be seen in Fig.10, the timings of experimental and analytical yielding almost coincide with each other, which verifies validity of the analytical procedure to judge yielding.

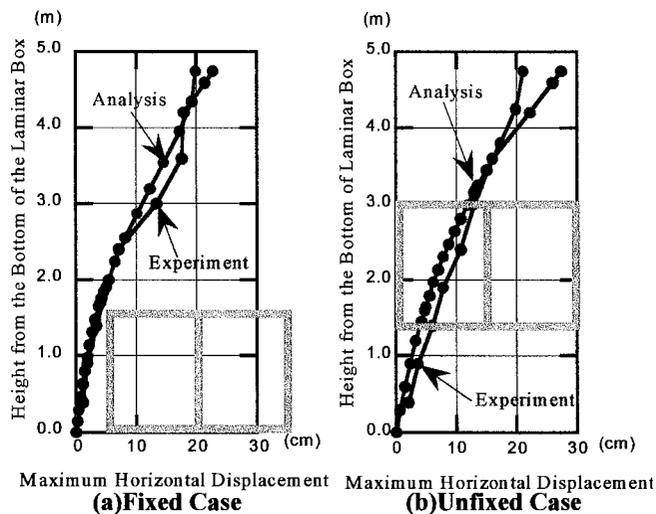


Fig.8 Maximum Value Distribution of Horizontal Displacement

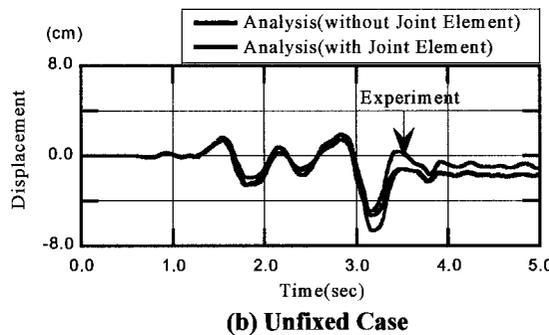
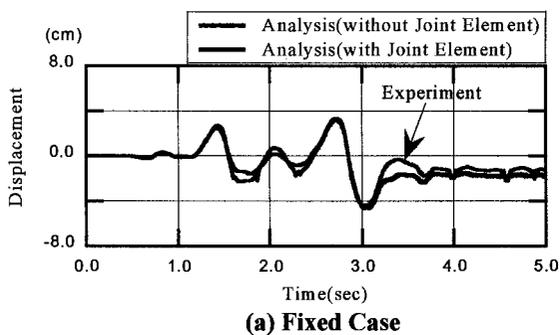


Fig. 9 Time Histories of Relative Displacement between Top and Bottom Slabs

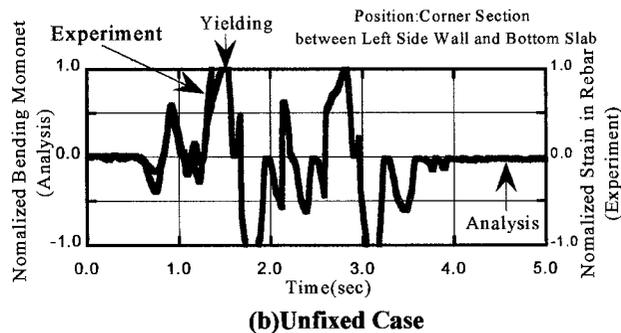
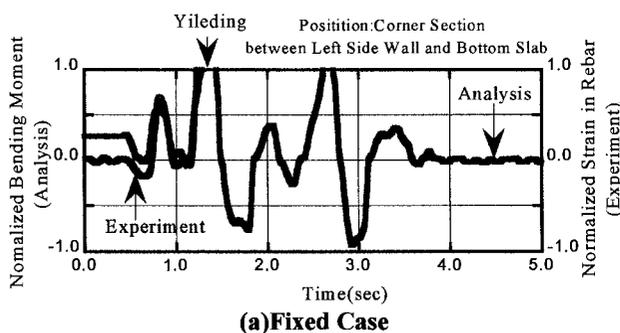
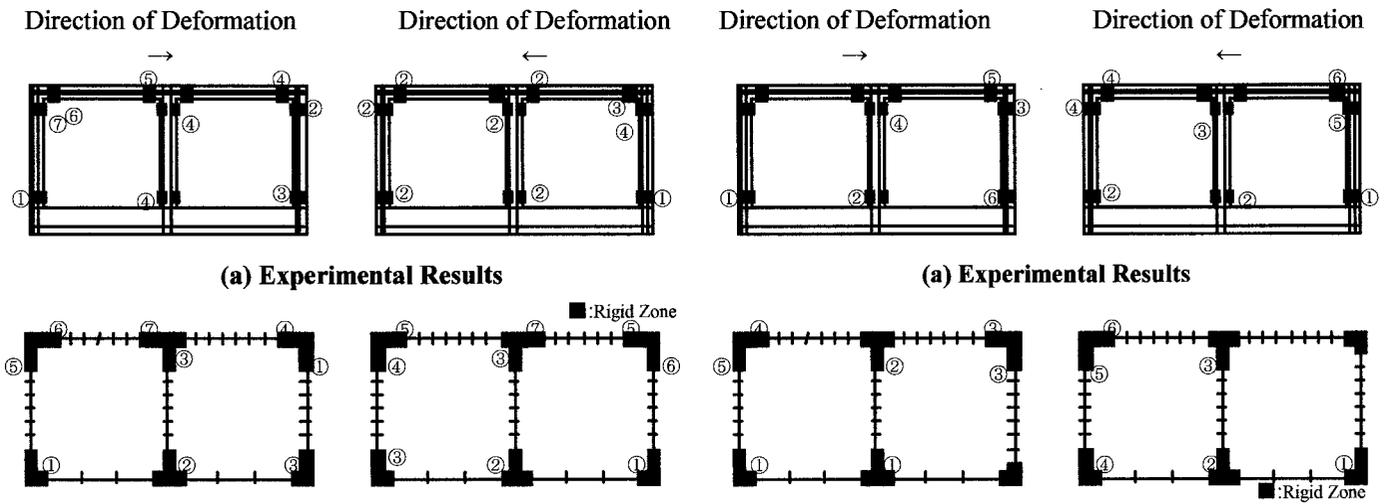


Fig.10 Time Histories of Steel Strain (Experiment) and Moment (Analysis) as Measure for Judgment of Yielding Relative Displacement between Top and Bottom Slabs

### 3) Positions and Time Order of Yielding in Steel

Fig.11 and 12 show the analytical results about distribution of yielding positions in the RC structures, which were compared with experimental ones in both cases. In Fig.11 and 12, the number in circle indicates the time order of yielding. Concerning the time order of yielding, some discrepancies were observed between analytical results and experimental ones. But since the time-lag between them was of negligible order. The position as well as the distribution in yielding process agrees well with those of experiments.



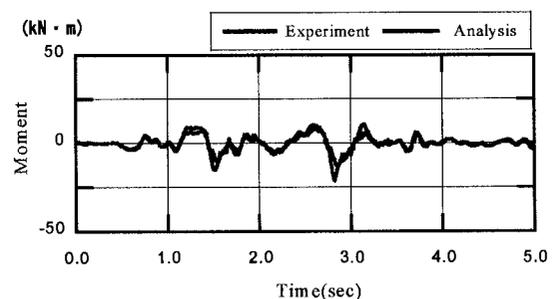
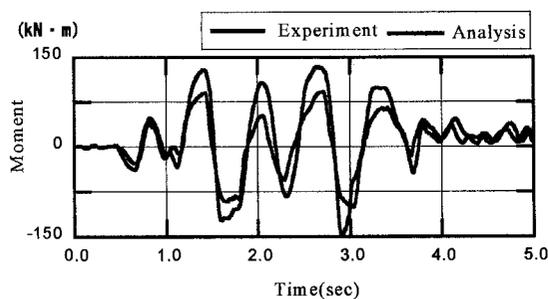
**Fig.11 Positions and Time Order of Yielding in Steel (Fixed Case)**

**Fig.12 Positions and Time Order of Yielding in Steel (Unfixed Case)**

### DISCUSSIONS ON OTHER IMPORTANT MEASURES FOR SEISMIC PERFORMANCE

#### Identification of Load Exerting Dominant Influence upon Displacement of RC Structure

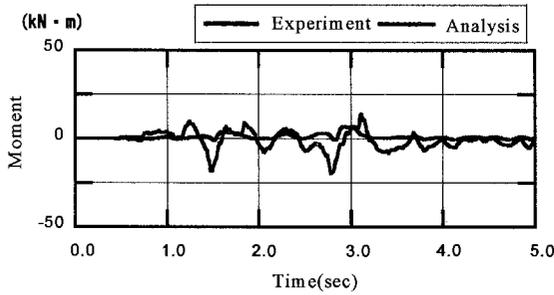
One of the important features of underground structure is that it is subject to a few kinds of loads. Three types of such loads are conceivable; 1) Shear stress acting on the top slab (load A), 2) Inertia force acting to structure (load B), and 3) Normal earth pressure acting on the side wall (load C). To understand quantitatively the contribution of each load, on the equal basis, we calculated the equivalent moments caused by the each load with respect to the center of bottom slab as showed in Fig.13 and 14. The effect of load A was found to be most dominant, which was also verified by analysis. As for loads B and C, the degree of their influence is much less than that of load A. Correlation between analytical and experimental equivalent moments for the inertial force (load B) seems satisfactory, but that for the normal earth pressures acting to the end walls (load C) cannot be judge as good. The discrepancy does not pose a problem in view of the small absolute values of load C compared with load A. The problem is that for normal earth pressure the analysis could not simulate the experimental measurement with time. This is caused by the limitation of the R-O model we applied.



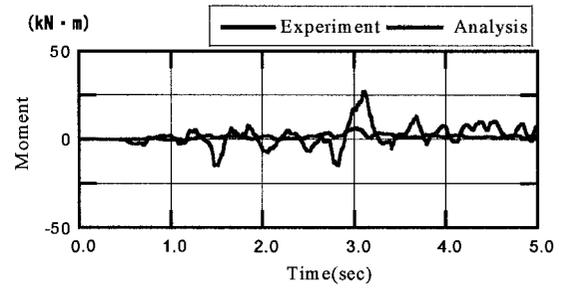
**(a) Moment by Shear Stress Acting on Top Slab**

**(b) Moment by Inertia Force Acting to RC Structure**

**Fig.13 Time History of Moment Caused by Three Kinds of Loads (Fixed Case)**



(c) Moment by Normal Earth Pressure Acting on the Left Side Wall



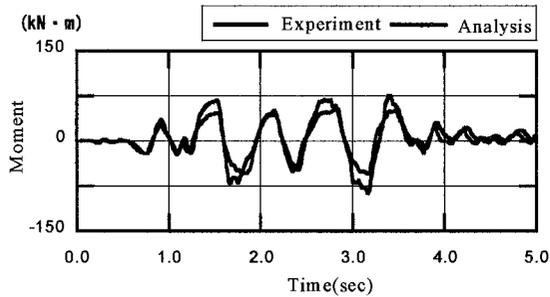
(d) Moment by Normal Earth Pressure Acting on the Right Side Wall

Fig.13 Time History of Moment Caused by Three Kinds of Loads (Fixed Case)

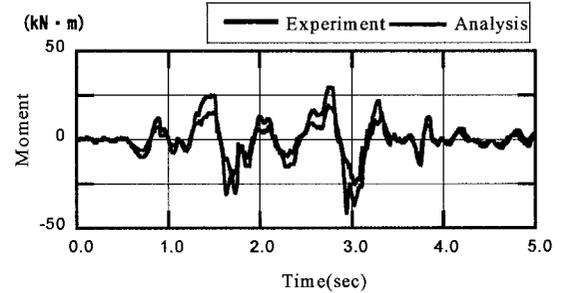
### Index about Plastic Deformation of RC Structure

We evaluated various indices of plastic deformation of RC structures. In Earthquake Resistant design specification authorized by JSCE adopts displacement ductility factors. Table 3 summarized experimental as well as analytical values of these ductility factors and deformation angles, which are based on relative displacement between top and bottom slabs normalized by the height of structure. As mentioned before, the parameters for R-O model were determined based on maximum strain level in soil encountered in the experiment. This might have led to substantial over-estimate of displacement at the time of initial yielding. In other words, the analytical method applied is more suited for the post-yielding range. For this specific embedded structure, maximum relative displacements or deformation angles are considered to be more practical than ductility factors normally employed as can be judged from the values in Table 3.

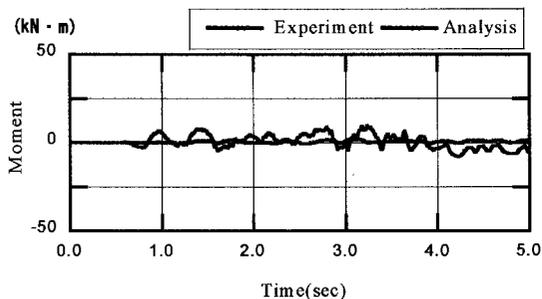
### CONCLUDING REMARKS



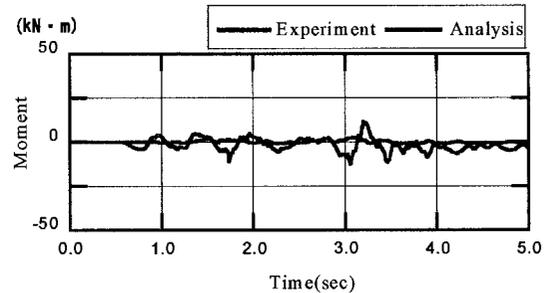
(a) Moment by Shear Stress acting on Top Slab



(b) Moment by Inertia Force acting to RC Structure



(c) Moment by Normal Earth Pressure Acting on the Left Side Wall



(d) Moment by Normal Earth Pressure Acting on the Right Side Wall

Fig.14 Time History of Moment Caused by Three Kinds of Loads (Unfixed Case)

We simulated large-scale laminar shear box excitation tests by dynamic nonlinear FEM, in which soil and RC structure

were defined as macro models. The conclusions are as follows.

(1) Soil and RC member were modeled as hysteresis dependent R-O and axial force dependent degrading tri-linear model, respectively. Analytical results were confirmed to reproduce the damage features of the RC structures, which were embedded in soil and subjected to dynamic earthquake load in terms of yielding in steel, dominant forces to deform the structures etc..

(2) In the case when shear stiffness of embedded RC structure is substantially smaller than that of soil, relative slippage and separation between soil and structure was thought to exert an insignificant influence on overall deformation of structure. But experimental and analytical results strongly suggested this effect of relative movement could not be ruled out on the deformation of structure especially in severe earthquakes.

(3) For a measure of post-yielding deformation, absolute relative deformations or deformation angles of underground duct-type RC structures are more appropriate than ductility factors currently used in Japan.

**Table 3. Evaluation of Indices for Verification of Seismic Performance  
(a) Fixed Model**

Index			Experiment	Analysis
Displacement in Rebar Yield	$\delta y$	[cm]	0.39	0.67
Maximum Displacement	$\delta \max$	[cm]	4.38	4.61
Ductility Factor	$\delta \max / \delta y$	-	11.24	6.88
Deformation Angle	$\delta \max / H$	[%]	3.63	3.41

**(b) Unfixed Model**

Index			Experiment	Analysis
Displacement in Rebar Yield	$\delta y$	[cm]	0.40	0.90
Maximum Displacement	$\delta \max$	[cm]	4.92	5.30
Ductility Factor	$\delta \max / \delta y$	-	12.30	5.89
Deformation Angle	$\delta \max / H$	[%]	3.64	3.93

H: Height of RC Structure

## ACKNOWLEDGEMENT

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